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ABSTRACT

A bibliography with approximately 1,000 references to articles on multidimensional scaling (MDS) is preceded by a summary review tracing the major developments in the areas covered, and identifying significant references in each. With the exception of a few earlier documents, the period covered is 1966 to 1978. Topics mentioned in the summary review include: indirect metric MDS; direct metric MDS; distance versus content models; metric versus nonmetric approaches; nonmetric MDS; individual differences MDS; conjoint measurement approach; dual (optional) scaling approach; evaluative studies of nonmetric MDS; and other topics. A large number of relevant computer programs, articles, and books are mentioned, including some books on cluster analysis, a topic which is otherwise omitted from the bibliography. (CTM)

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MULTIDIMENSIONAL SCALING: A HISTORICAL SKETCH AND BIBLIOGRAPHY

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by

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PREFACE

This report presents a summary of the bibliographic information gathered for the author's recent projects (the Canada Council Grant No. 73-0399; the National Research Council Grant No. A4581; OISE Small-Scale Project Grant No. 3571). Most information was originally collected to write three review articles (Nishisato, 1977, 1978, 1978), but could not fully be used in these articles due to the limited space in the journals. The main purpose of this report is, therefore, to present the gathered information in full and to make it available for those interested. The bibliographic information covers mainly the past 12 years up to February, 1978. This bibliography is by no means complete, or rather it is more truthful to say that a number of relevant articles, even obvious ones, may be missing. From the users' point of view, the articles in the bibliography should have been categorized into subgroups in terms of their contents. This, however, was not done because of the difficulty in establishing a straightforward convenient classification scheme and possibility of repeated listings of the same articles in different subgroups.

The report is divided into two parts. Part I presents a brief description of each of the selected topics in multidimensional scaling (MDS), which it is hoped may serve as a helpful introduction to the history of MDS. Part II presents a bibliography of MDS literature, covering the so-called metric and nonmetric MDS, conjoint measurement analysis and dual (optimal) scaling.

The author has received with cordial appreciation many reprints and useful information from (alphabetically) Drs./Messrs. T. W. Anderson, H. Aoyama, P. Arabie, B. Bloxom, B. Bolton, R. A. Bradley, M. Browne, J. D. Carroll, N. Cliff, C. H. Coombs, L. G. Cooper, M. C. Corballis, H. A. David, J. de Leeuw, H. Eisler, B. S. Everitt, R. F. Fagot, J. C. Falmagne, S. E. Fienberg, P. C. Fishburn, L. A. Goodman, B. F. Green, Jr., P. E. Green, M. Greenacre, R. A. M. Gregson, L. Guttman, C. Hayashi, M. J. R. Healy, E. W. Holman,

J. L. Horn, Y. Inukai, P. D. Isaac, S. Iwatsubo, R. M. Johnson, L. E. Jones, K. G. Jöreskog, J. R. Kettering, D. H. Krantz, W. Kristof, J. C. Lingoes, F. M. Lord, R. D. Luce, R. C. MacCallum, G. H. McClelland, L. L. McQuitty, H. C. Micko, J. C. Ogilvie, J. P. N. Phillips, J. O. Ramsay, E. E. Roskam, W. Rozeboom, T. Saito, G. Saporta, P. H. Schönemann, F. Sixtl, L. Sjöberg, V. Srinivasan, H. Thomas, A. Tversky, L. J. Th. van der Kamp, E. J. Williams, H. Yanai, F. W. Young, and D. W. Zimmerman. It is regretted that this report and the aforementioned review articles could not present valuable information, contributed by those mentioned above, about such areas as theories of test scores, theories of measurement, factor analysis, analysis of covariance structures and clustering techniques.

Cordial appreciation is also extended to Mrs. Patricia O'Connor for typing the final report and to Mrs. Gloria Powell for typing earlier drafts of the bibliography.

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* The publications program of The Ontario Institute for Studies in Education has been established to make available information and materials arising from studies in education, to foster the spirit of critical inquiry, and to provide a forum for the exchange of ideas about education. The opinions expressed should be viewed as those of the contributors.

[Part I]

MULTIDIMENSIONAL SCALING:

A HISTORICAL SKETCH

Shizuhiko Nishisato

1. Introduction

The term "scaling" refers in general to a procedure that transforms data into mathematically well-defined. quantitative measurement. It is often used interchangeably with "quantification method," and refers to a family of techniques. In the history of scaling, one sees Fechner's monumental work "Elemente der Psychophysik" (1860), Thurstone's epoch-making work on the law of comparative judgment (1927), and thereafter an ever-increasing number of publications on scaling. In retrospect, however, that steady progress looks just like a subliminal response process of certain nerve cells before sudden break into an overt response. This analogy of the all-or-none phenomenon is by no means intended to lessen the importance of the earlier studies, but rather to emphasize an explosive manner in which new ideas of scaling and an enormous number of studies have been published during the past two decades.

The recent developments have been both divergent and convergent--divergent in the sense that a wide variety of approaches and applications have been presented by investigators from diverse disciplines and convergent in the sense that research has also been focussed on clarifying relations among different techniques and unifying them under a general framework. Another aspect which characterizes the recent developments lies in the fact that a number of computer programs have formally or informally been published and made available for researchers. This has facilitated to an immeasurable extent advancement of scaling methodology both in theory and practice. If one is to choose a phrase that best described the current scene of research on scaling, it seems that "multidimensional scaling" would be an indisputable choice.

Multidimensional scaling, as termed here and abbreviated as MDS, refers to a wide variety of techniques which derive from relational data a multi-dimensional configuration (i.e., sets of orthogonal coordinates) of stimuli and/or subjects. As such, it includes not only those well-known metric and

nonmetric techniques and their variants, but also multidimensional extensions of unidimensional scaling procedures and other types of multidimensional quantification techniques.

Let us now look at early studies which provided MDS methodology with foundations. At the turn of this century, Karl Pearson considered the problem of linear combinations of n variables so as to represent a set of variables in a space of smaller (<n) dimensionality. This is essentially the same as the technique later systematized under the name of principal component analysis (PCA) by Hotelling (1933). In this study, Hotelling presented an application of the eigenvalue theory to deriving an efficient procedure for data reduction, which provided a basic principle of analysis to many variants of MDS techniques. In the 1930's, there appeared two more studies which were equally as important as PCA for laying foundations for MDS methodology. The first one is the matrix decomposition theorem by Eckart and Young (1936), which is often referred to as singular value decomposition (SVD). This theorem clarified how a data matrix could be decomposed into the row structure and the column structure , and this provided a basis for a variety of individual differences scaling, including dual (optimal) scaling. It has also served as a versatile tool to simplify algebraic manipulations of matrix equations. The second one is a set of theorems by Young and Householder (1938). The theorems provided means to test whether the positions of the stimuli could be represented in a real Euclidean space, to determine the dimensionality of the space and to calculate the coordinates of the stimulus points.

There is no doubt that these early studies have helped many investigators develop a number of MDS techniques. Other than these, one can find at least two more groups of studies which have had similar and equally important impact on the development of MDS methodology. The first one is a series of studies on nonmetric scaling by Coombs and his associates in the 1950's, which culminated into Coombs'

book (1964). It seems that these studies have contributed to the readiness of scientific knowledge, which led to Shepard's breakthrough in nonmetric MDS, presented in 1962. The second one is extensive research on conjoint measurement, initiated by Luce & Tukey (1964), and then pursued by many followers. This group of research has provided a general principle or framework for integrating a wide range of scaling techniques.

These may be regarded as major undercurrents in the history of MDS scaling which have steered vast research endeavors into what we now know as "main streams" in scaling. Part I of this report is not intended to present a review of MDS studies, but to summarize some focal points in research as a possible aid for users of Part II: Bibliography. The order in which the topics are presented below does not reflect any historical precedence or order of importance.

2. Metric MDS (I)

Following the foundations laid by Richardson (1938) and Young & Householder (1938), Torgerson (1952) presented the first complete formulation of the so-called (indirect) metric MDS procedure, which may be summarized as follows:

(1) Collect pair-wise similarity measures between stimuli j and k, s_{jk}, or else, derive s_{jk} from non-pair-wise similarity data.

(2) transform s_{jk} into inter-stimulus (relative) distances, h_{jk}, such that

$$h_{jk} = d_{jk} + c,$$

where d_{jk} are distances between stimuli j and k, and c is the so-called (unknown) additive constant.

(3) Calculate a matrix of scalar products from d_{jk}, with the origin at the centroid of the stimulus configuration, $B^* = (b^*_{jk})$, where

$$b^*_{jk} = \frac{1}{2}\left[\frac{1}{n}\sum_j^n d^2_{jk} + \frac{1}{n}\sum_k^n d^2_{jk} - \frac{1}{n^2}\sum_{jk}^{nn} d^2_{jk} - d^2_{jk}\right],$$

and n is the total number of stimuli.

(4) Decompose B^* as

$$B^* = X\Lambda X' = (X\Lambda^{\frac{1}{2}})(\Lambda^{\frac{1}{2}}X') = AA' ,$$

where Λ is the txt diagonal matrix of the t eigenvalues of B^*, X is the matrix of the corresponding eigenvectors in columns, and A is the nxt matrix of rectangular coordinates of n stimuli on t axes.

From the user's point of view, there are two problems:

(a) How to obtain s_{jk}---Refer, for example, to Richardson (1938), Abelson (1954), Messick (1956), Torgerson (1958), Indow & Kanazawa (1960), Indow & Uchizono (1960) and Ekman (1963).

(b) How to determine c (i.e., the additive constant problem)---The first systematic study was presented by Messick & Abelson (1956). Cooper (1972) derived a least-squares estimate of c, using the Fletcher-Powell routine. LUeur & Fillbrandt (1969) and Kristof (1976) also presented relevant studies. In the area of individual differences MDS, this problem has been solved by Bloxom (1968), Carroll & Chang (1970), Krane (1976), and Takane, Young & de Leeuw (1977).

3. Metric MDS (II)

When relative distances, h_{jk}, are obtained from data, Torgerson's approach, discussed above, uses the so-called discriminal dispersion as the unit of the scale. Furthermore, one must solve the additive constant problem to calculate d_{jk} from h_{jk}. Although these two aspects may or may not be serious problems for Torgerson's approach, there is another approach, which is free from these probable problems. The approach is often referred to as Ekman's direct multidimensional ratio scaling. The procedure of this approach may be summarized

as follows:

(1) Subjects are asked typically "How much of the attribute of stimulus j (e.g., orange color) is contained in the attribute of stimulus k (e.g., red color)?" The response is given in terms of proportion (e.g., 0.7), q_{jk}.

(2) Stimuli j and k are conceptualized as two vectors extending from the origin with angle ϕ_{jk} and lengths h_j and h_k, respectively. The length of a vector indicates intensity of the stimulus, and hence generates quantitative differences among stimuli, while the angle between two vectors indicates qualitative difference between the stimuli. q_{jk} then is interpreted as the ratio of the projection of vector j on vector k to the length of vector k, h_k, that is,

$$q_{jk} = \frac{h_j \cos\phi_{jk}}{h_j} = \left(\frac{h_j}{h_k}\right) \cos\phi_{jk} \quad .$$

(3) Obtain the scalar product of the two vectors,

$$b_{jk} = h_j h_k \cos\phi_{jk} = q_{jk} h_k^2 \quad .$$

where h_k^2 are unknown.

(4) Consider a matrix, of which the element in the j-th row and the k-th column is given by

$$\frac{q_{jk}}{q_{kj}} = \frac{h_j^2}{h_k^2} \quad .$$

The sum of the j-th row of this matrix is $h_j^2(1/\Sigma h_k^2)$ so that if the unit of the scale is so chosen as $(1/\Sigma h_j^2) = 1$, one can calculate h_k^2 in Step (3), and hence b_{jk}.

(5) The matrix of scalar products, B, = (b_{jk}), can now be decomposed as

$$B = U\Lambda U' = (U\Lambda^{\frac{1}{2}})(\Lambda^{\frac{1}{2}}U)' = AA' \quad ,$$

where A is, as discudded in Section 2, the matrix of coordinates of n stimuli on t axes.

Micko & Lehmann (1969) presented two least-squares estimation procedures of b_{jk} and h_k^2. Micko (1970) presented a "halo" model, an alternative to Ekman's model.

4. Distance versus Content Models

The two approaches, described in Sections 2 and 3, are representative of the two types of MDS models, that is, the distance model and the content model, of the classification scheme proposed by Ekman & Sjöberg (1965). The distance model considers similarity of two stimuli as a function of differences in perceived attributes of the stimuli, represented as distances in the judgmental space. In terms of the kinds of function used, one can introduce another classification scheme, which divides MDS into metric and nonmetric approaches (this will be discussed later). As will be seen later, the majority of MDS methods belong to the category of distance model. The content model considers similarity of two stimuli as the ratio between a measure of commonality and a measure of totality, as seen in Ekman's method. Within this framework, a number of similarity models have been proposed with mixtures of varying degree and modes of quantitative and qualitative variations, h_j and ϕ_{jk}. See, for example, Ekman & Lindman (1961), Ekman, Engen, Lindman & Künnapas (1964), Goude (1966), Eisler (1967), Micko (1970), Waern (1970, 1971), Ekehammar (1972), Eisler & Roskam (1973, 1977), Lund (1975) and Sjöberg (1976). Eisler & Roskam (1977a, b) presented another dichotomization of MDS models, E-model (the vector model, a modified content approach) for commonality ratio ratings and multidimensional ratio ratings, and R-model (the distance model) for similarity ratings.

5. Metric versus Nonmetric Approaches

The metric approach regards the input data as interval or ratio measurements, and analyzes the data (numerical values) directly, as seen in Torgerson's and Ekman's methods. The nonmetric method, which is also referred to as ordinal method (Beals, Krantz & Tversky, 1968), uses the rank order of the input data, thus regarding them as ordinal measurements. In general, however, both approaches assume the same metric space for the output configuration of stimulus points, and provide highly comparable results. By virtue of the weaker assumption about the input measurement, the nonmetric approach is less susceptible, at least computationally, to the problem arising from missing responses.

6. Nonmetric MDS

Shepard's first practical nonmetric MDS procedure (1962) is often regarded as a breakthrough in MDS methodology. To put nonmetric MDS on a firm mathematical basis, Kruskal (1964) incorporated important refinements in Shepard's approach, leading to what is often called the Shepard-Kruskal approach. To date, a number of nonmetric MDS procedures for similarity data have been proposed, of which general underlying idea may be stated as follows:

Given $n(n-1)/2$ measures of pair-wise similarity of n stimuli, s_{jk}, we generate rank socres δ_{jk} from s_{jk} (δ_{jk} are ranks of s_{jk}). The task is to find A (a matrix of coordinates of n stimuli on t axes) of minimum dimensionality t such that

$$d_{jk} \geq d_{sr} \quad \text{whenever} \quad \delta_{jk} > \delta_{sr} \ ,$$

where d_{jk} and d_{sr} are distances, calculated from $A = (a_{jm})$, for example,

$$d_{jk} = \left[\sum_{m=1}^{t} |a_{jm} - a_{km}|^{p} \right]^{\frac{1}{p}} , \quad p \geq 1 \ .$$

To carry out this task, a general procedure may be summarized as follows:

(a) For a given dimensionality, select an initial configuration, A_0.

(b) Compute d_{jk} between vectors $\underline{a}_j$ and $\underline{a}_k$ of A_0, and also computer <u>appropriate distances</u> $\hat{d}_{jk}$, chosen to be as close as possible to d_{jk}, subject to being monotone to δ_{jk}.

(c) Evaluate the goodness of fit, as reflected on, for example, discrepancies between d_{jk} and $\hat{d}_{jk}$, or discrepancies between A and $\hat{A}$ (predicted A).

(d) If the goodness-of-fit index exceeds a specified tolerance level, search for a new configuration, A_1, which provides a better fit.

(e) Repeat the process until successive configurations, A_0, A_1, A_2, ..., A_v converge.

(f) Repeat the above process with the configuration of different dimensionality.

(g) Choose the lowest dimensional configuration for which the goodness of fit is satisfactory.

The computation of appropriate distance $\hat{d}_{jk}$ in Step (b) is a core of the nonmetric procedures. There are two methods in general use. The first one is called <u>monotone regression</u> (see, for example, Kruskal, 1964, Roskam, 1968; Barlow, Bartholomew, Brenner & Brunk, 1972; Young, 1972), and the second one is <u>Guttman's rank-image permutation</u> (see, for example, many articles by Lingoes, in particular, Lingoes, 1977; Guttman, 1968). The first one starts with a given set of individual points, joins the points into a block, and combines the blocks until the block means attain a monotone order. Studies relevant to this have been conducted by Roskam (1969), Kruskal (1971), Lingoes (1971), McDonald (1976) and de Leeuw (1977). The second one is a direct permutation of individual points into a monotone order. This algorithm has been investigated by Gleason (1967), Guttman (1968), Roskam (1969, 1971),

Lingoes & Roskam (1973), de Leeuw (1975, 1977), and de Leeuw & Heiser (1977), which put the algorithm on a firm numerical and theoretical basis.

A variety of nonmetric MDS procedures have been proposed by, among others, Guttman & Lingoes (see, for example, Lingoes, 1972), McGee (1966), Young & Torgerson (1967), Gleason (1967), de Leeuw (1968), Roskam (1968), Hayashi (1974), and Takane, Young and de Leeuw (1977). Although these are different among themselves with respect to formulations, flexibility of options, starting configurations, algorithms and so on, they are generally expected to produce highly comparable results.

7. Individual Differences MDS (I)

One of the most attended topics in MDS during recent years is the so-called individual differences MDS. Insread of determining just the stimulus configuration as perceived by the "average" subject, this approach starts with the assumption that each subject (or a subgroup of subjects) may have a unique judgmental space (e.g., the perceptual color space of a color blind subject may be somewhat twisted). Tucker & Messick (1963) presented a procedure called "points of view" (POV) analysis. This procedure first analyzes similarity data, and classifies subjects into homogeneous subgroups. Each of these then is analyzed by MDS to obtain the stimulus configuration for each "point of view." See discussions on POV by Ross (1966) and Cliff (1968). The other methods to be mentioned below subject the entire data to analysis of both stimuli and subjects. The procedure developed by McGee (1968) allows a different configuration for each subject, but puts constraints on how different the configurations may be. The procedure presented by Kruskal (1968) either forces a single configuration but allows different distance functions, or allows different configurations but forces a single distance function. Bloxom (1968), Horam (1969), and Carroll & Chang (1970) independently proposed the following distance model,

$$d_{jk}^{(i)} = \sqrt{\sum_m w_{im}(a_{jm}-a_{km})^2}$$

where $d_{jk}^{(i)}$ is the distance between stimuli j and k, as perceived by subject i, and w_{im} is the weight of subject i on axis m. To solve the problem, Bloxom used the method of steepest descent, which was later replaced by Jöreskog's ACOVS (analysis of covariance structure algorithm) for faster computation (Bloxom, 1974). Horan presented a way to combine data from different subjects without distorting nonlinearly the configuration of stimuli, but did not provide a way to calculate subjects' weights on different dimensions. Then, the most successful method, up to 1970, was presented, that is, INDSCAL, by Carroll & Chang, which was based on an N-way (3-way) generalization of the Eckart-Young singular value decomposition, called CANDECOMP. Carroll & Chang used the alternating least-squares method, to solve the problem. Their solution is unique in the sense that there is no freedom for rotation of axes. However, Carroll & Chang (1972) later restored the rotational freedom in the procedure called IDIOSCAL.

A far more general model than INDISCAL was proposed by Tucker (1972). His three-mode scaling, however, provided only an approximation to a least-squares solution, while INDSCAL yielded a least-squares fit. A model similar to Tucker's was Harshman's PARAFAC-2 model (1972, 1976), in which a common oblique reference system was postulated for the entire group of subjects rather than different systems for different subjects as in Tucker's model. Schönemann (1972) presented a general model, called subjective metrics model, and provided an elegant algebraic solution for infallible data, which, without any loss function, was limited in its applicability to real data.

From the computational point of view, we see a linear programming approach by Srinivasam & Shocker (1973), Krane's simultaneous estimation of parameters, including the additive constant, a fast algorithm called COSPA (common space analysis) by Schönemann, Carter and James (1976, 1977), an evaluation technique called PINDIS (Procrustean individual differences scaling) by Borg & Lingoes (1976; see also Lingoes, 1977), which uses Procrustean transformations (Schönemann, 1966; Schönemann & Carroll, 1970; Lingoes & Schönemann, 1974; Gower, 1975), Ramsay's maximum likelihood procedure (1977), de Leeuw's method (1977) based on use of convex functions, and Heiser's metric and nonmetric method (1975), using de Leeuw's algorithm.

If one is to seek the second breakthrough, after Shepard's (1962), in the history of MDS methodology, it would be the study by Takane, Young & de Leeuw (1977). While most of the methods mentioned so far have rather strict data restrictions (e.g., the data matrix be symmetric, without missing observations, unreplicated, unconditional, defined at least at the level of interval measurement). Takane-Young-deLeeuw's ALSCAL does not impose these restrictions on the data. In consequence, ALSCAL is both metric and nonmetric, and it is claimed to be the **first** successful and satisfactory nonmetric individual differences MDS. There were some previous attempts for nonmetric procedures by Carroll & Chang (1970, 1974), Yates (1972) and Young. ALSCAL is robust in terms of recovery of the input data, flexible with respect to types of data and levels of measurement, and computationally fast.

8. Individual Differences MDS (II)

Individual differences MDS has also been investigated for dominance data such as ranking and paired comparison preference data. One can identify at least three groups of research. The first one is what is often called the vector model of preferential choice, investigated by Tucker (1960, 1968), Slater (1960),

Carroll & Chang (1964, 1968), Bechtel (1969), Bechtel, Tucker & Chang (1971) and Carroll (1972). The second one is the multidimensional unfolding model, investigated by Lingoes (1966), Carroll & Chang (1967), Young (1968, 1969, 1972), Schönemann (1970), Schönemann (1972), Schönemann & Wang (1972), Davidson (1972, 1973), Gold (1973), Srinivasan & Shocker (1973), and Wang, Schönemann & Rusk (1975). The relation between the vector model of preferential choice and the unfolding model has been investigated by Coombs & Kao (1960), Ross & Cliff (1964), Cliff (1968, 1969), Davidson (1973), Coombs (1975), Davison (1976), and Davison & Jones (1976). The third approach is that of dual (optimal) scaling, investigated by Guttman (1946), de Leeuw (1973), and Nishisato (1976). The relationship between the dual scaling approach and the vector model was studied by Nishisato (1978). Excellent discussions on individual differences MDS of preference data can be found in Carroll (1972), Carroll & Wish (1974), and Roskam (1977).

9. Conjoint Measurement Approach

As a part of axiomatic measurement theory, conjoint measurement was extensively studied in the 1960's (see, for example, articles by Fishburn, Holman, Krantz, Luce, Suppes, Tukey, and Tversky). Conjoint measurement analysis aims to quantify "basic" categorical variables in such a way that the sum (additive conjoint model) or the product (multiplication conjoint model) of the quantified basic variables may explain the order (e.g., preference order) of the complex "compound" variables given as data. When the number of basic categorical variables is greater than two, the model is referred to as the polynomial conjoint model. Algorithms of conjoint analysis have been discussed by Goode (1964, 1967), Young (1969, 1972, 1973), Johnson (1972), Lingoes (1973), Green (1973), Srinivasan & Shocker (1973) and Carroll (1976). Trade-off analysis which is a variant of conjoint analysis using paired comparison data rather than ranking data, has been put into practical use in analysis of

consumer behavior (see, for example, Johnson, 1972, 1974; Westwood, Lunn & Beazley, 1974). Tversky (1967) investigated the generality of a polynomial conjoint model and presented examples of polynomial conjoint combination rules, including the performance models of Hull and Spence, the Bradley-Terry-Luce choice model, Savage's subjective expected utility model and nonmetric MDS models. In a series of studies on POLYCON (Young, 1969 ∿ 1973), Young extended the polynomial conjoint approach, and showed, through the generalizations and the specifications of the nonmetric MDS approach and the Minkowski power-metric function, that his general model could handle such submodels as Minkowski scaling, multidimensional unfolding, polynomial conjoint measurement, nonmetric factor analysis, the Bradley-Terry-Luce choice model and Savage's subjective expected utility model.

10. Dual (Optimal) Scaling Approach

As Hill (1974) called this approach "a neglected multivariate method," researchers in different disciplines adopted different names for it, which is essentially an application of the Eckart-Young singular value decomposition to categorical data. Some of the names adopted for this approach are the method of reciprocal averages (Horst), appropriate scoring (Fisher), additive scoring (Fisher), Guttman weighting, canonical scoring, analyse factorielle des correspondances (Benzécri), correspondenc analysis (Hill), principal component analysis of qualitative data (Torgerson), optimal scaling (Bock), simultaneous linear regression (Lingoes), biplot (Gabriel) and dual scaling (Nishisato). In 1933, Richardson and Kuder discussed a basic idea, which was further elaborated by Horst (1935). It seems, however, that the first rigorous mathematical formulation of dual scaling was presented by Hirschfeld (1935), which may be called the simultaneous linear regression approach. Following Fisher (1940), Maung (1941) presented the bivariate correlational, the canonical correlational

and the one-way-analysis-of-variance approaches to dual scaling. Guttman (1941) presented a thorough formulation of dual scaling as applied to multiple choice data. Guttman (1946) applied this approach to paired comparison and ranking data. Mosier (1946) used an IBM machine for the approach called the method of reciprocal averages. Fisher (1948)applied dual scaling to the analysis of variance of non-numerical data. In spite of these sound studies in the 1930's and 40's, dual scaling has taken a long way to draw attention of many investigators. Some of the main streams of research in the 1950's and 60's were a series of studies (scaling of similarity matrices, paired comparison matrices, sociometry matrices, tournament matrices, multidimensional matrices) by Hayashi and his associates, conducted under the rubric of Hayashi's theory of quantification, studies by Benzécri and his associates in the 1960's, which culminated into the second volume of "L'Analyse des Données" in 1973, studies by Bock (1956, 1960), a thorough mathematical exposition by Lancaster (1958), Torgerson's presentation (1958), Lord's study on reliability (1958), Kendall & Stuart's exposition of canonical analysis of a two-way contingency table, a study on ordered categories by Bradley, Katti & Coons (1962), Kruskal's additive analysis of variance (1965), studies by Shiba (1965, 1965), Lingoes' simultaneous linear regression (1963, 1968), and McDonald's unified treatment of weighting problem (1968). In the 1970's, the number of publications on dual scaling has suddenly increased and the applications of dual scaling have greatly been expanded. Some of the contributors are Benzécri, Hayashi, de Leeuw, Young, Takane, Hill, Nishisato, Gabriel, Saporta, Carroll, Inukai, Iwatsubo, Saito, Torii, Yoshizawa, Teil, Healy and Goldstein. A few books on data analysis devoted chapters and a number of pages on dual scaling (Hayashi, Higuchi & Komazawa, 1971; Takeuchi & Yanai, 1972; Benzécri and others, 1973; Lingoes, 1973; Nishisato, 1975).

11. Evaluative Studies of Nonmetric MDS

In the MDS literature, one can find an overwhelming number of articles on nonmetric MDS. There have been some attempts to compare different procedures on a theoretical basis (e.g., Gleason, 1967; Young & Appelbaum, 1968; Guttman, 1968; Roskam, 1969). But, in most cases, the investigators have evaluated and compared nonmetric procedures by Monte Carlo computations. This has been so because the nonmetric procedures do not provide a solution in a closed form but in the manner of successive approximations. Studies which are often referred to include those by Shepard (1966), Sherman & Young (1968), Klahr (1969), Stenson & Knoll (1969), Wagenaar & Padmos (1969), Young (1970), Carroll (1970), Spence (1970, 1972), Lingoes & Roskam (1973), Domoney (1973), Spence & Ogilvie (1973), Cohen & Jones (1974), Isaac & Poor (1974), Spence & Domoney (1974), Girard & Cliff (1976), McDonald (1976), MacCallum & Cornelius (1977), and Takane, Young and de Leeuw (1977). These studies and others have examined such problems as statistical distributions of badness-of-fit measures, metric determinacy, robustness of procedures in relation to the existence of errors, efficiency of incomplete designs and relative merits of different procedures. Spaeth & Guthery (1969), Arabie (1973) and Clark (1976) also presented relevant studies.

12. Other Topics

(a) Nonmetric procedures are relatively free, at least computationally, from the effects of missing responses. This aspect, however, calls for systematic investigation if one is to economize the work involved in MDS. There are at least two ways to consider this problem. The first one is to consider efficiency in information retrieval of incomplete designs for data collection. See Domoney (1973), Spence & Domoney (1974), and Spence & Janssen (1974). Regarding data collection methods, refer also to Rosenberg, Nelson & Vivekamanthan (1968), and Fillenbaum & Rapoport (1971). When one deals with

massive data, one often disregards individual differences. The second one is to handle directly individual differences in an attempt to economize the data collection. This is the so-called ISIS (interactive scaling with individual subjects), investigated by Cliff & Young (1970), Young & Cliff (1972), Baker (1974), Baker & Young (1975), and Girard & Cliff (1976).

(b) One of the basic problems of MDS is to define similarity (dissimilarity) and distance functions. The concept of similarity has been investigated by those investigators of the content method, mentioned earlier. Other than those, one can find related work by Gregson (1970, 1975), Hosman & Künnapas (1972), and measurement-theoretic studies by Krantz (1967), Krantz & Tversky (1975), Tversky & Krantz (1970) and Schönemann (1977). Boyd (1972) discussed an information-theoretic distance measure, and Nishisato (1975) referred to the Rajski distance. There have been many studies on the Minkowski power-metric. See, for example, Shepard (1964), Cross (1965), Hyman & Well (1967, 1968), Thomas (1968), Wender (1968, 1969, 1970), Young (1968, 1972, 1973), Micko & Fischer (1970), Sherman (1970, 1972), Arnold (1971), Fischer & Micko (1972), Roskam (1972), Shepard & Cermak (1973), Eisler (1973), Arabie & Boorman (1973), Carroll & Wish (1974), and Lissitz & Robinson (1977).

(c) One of the most remarkable aspects of the recent MDS developments is dissemination of many computer programs. Bell Laboratories have produced many programs, among others, MDSCAL, INDSCAL, IDIOSCAL, MDPREF, PARAMAP, PREFMAP, MANANOVA, KYST, CCM and SIMULES, which were written mainly by Chang, Carroll, Kruskal, Shepard and Carmone. See articles by these investigators for details of practical information. The so-called Guttman-Lingoes series consist of over twenty programs, divided into SSA (smallest space analysis) series, MSA (multidimensional scalogram analysis) series and CM (conjoint measurement) series. See Lingoes (1973) for program listings and information for users. The L. L.

Thurstone Psychometric Laboratory has distributed such programs as TORSCA, ALSCAL, ADDALS, INDISCAL, MORALS, PRINCIPALS, SCALAR, KYST-2, POLYCON, ISIS and VIEWS, prepared by Young, Takane, de Leeuw, Baker and Levinsohn. See the Psychometric Laboratory Reports for detailed information. The University of Nijmegen has disseminated such programs as MNSSAOR, MNSAST, MNCPAEX, MNTRIX, MNRSAST, MNNFAEX, MNSTRUC, MRSCAL, ADDIT and UNICON, prepared mainly by Roskam and some by Roskam & Lingoes. Refer to the book edited by Lingoes (1977). There was close collaboration among investigators to integrate some programs, which resulted in the so-called MINI-series (MINI = Michigan-Israel-Netherlands-Integrated), consisting of MINI-SSA, MINI-CPA, MINI-TRI and MINI-RSA. The main investigators are Lingoes, Roskam and Guttman, with collaborators such as de Leeuw, Borg and Heiser. Other than these groups of programs, a number of individual programs have been made available, among others, McGee's DEMD-CEMD, Cooper's COSCAL, Schönemann-Carter-James' COSPA, Eisler's MCITYB, de Leeuw's HOMALS 1-3 and Ramsay's MULTISCAL. There are publications, which provide excellent compendia of computer programs. The appendix of Green & Carmone (1970) presents a sketch of many available programs. The appendix prepared by Carroll (1973) in Green & Wind (1973) is entitled "Models and algorithms for multidimensional scaling, conjoint measurement and related techniques," and is a highly informative, noteworthy article of 89 pages. Lingoes' book (1973) presents full information about Guttman-Lingoes program series. There must be many other important programs and useful documents, but a review of this area has to wait for the further work.

(d) Books on MDS have also contributed to the dissemination of various techniques. In the early part of the 1960's, the books by Torgerson (1958) and Coombs (1964) played the important role of being "main source books on MDS." In spite of the nonmetric breakthrough by Shepard (1962), it took several years before the

nonmetric procedure was dealt with in a book. In 1968, Roskam published a very informative book on nonmetric analysis. Application-oriented books were written by Green & Carmone (1970), Green & Rao (1972), and Green & Wind (1973). Major theoretical developments and exemplary applications of MDS, up to 1972, were published in two volumes, Volume I, Theory, edited by Shepard, Romney & Nerlove (1972), and Volume II, Applications, edited by Romney, Shepard & Nerlove (1972). Another excellent source book was published in 1977, edited by Lingoes, with contributors Borg, de Leeuw, Guttman, Heiser, Lingoes, Lissitz, Roskam & Schönemann. This book is oriented toward Guttman-Lingoes series, MINI-series and related developments in recent years. Benzécri and his associates (1973) published two volumes in French on data analysis, one of which was totally devoted to theoretical and practical explications of "correspondence analysis" (dual scaling). The book by Hayashi, Higuchi & Komazawa (1970) (in Japanese) covers a series of quantification techniques developed by Hayashi and his associates. The book by Takeuchi & Yanai (1972) (in Japanese) discusses dual scaling in the context of general multivariate analysis. The book by Nishisato (1975) (in Japanese) covers a wide variety of scaling techniques in thirteen chapters, of which three are devoted to dual scaling, metric MDS and nonmetric MDS. There are other relevant books such as Golledge & Rayner (1977?), Delbeke (1968; see Carroll's review, 1970), Krantz, Luce, Suppes & Tversky (1971), and Green (1976, 1977). Although the dates of the publications are unknown, there seem to be many books being planned or prepared for publication, to name a few, a book on MDS by Carroll, Green, Kruskal, Shepard & Wish, another book on MDS by Young, de Leeuw & Takane, and a book on dual scaling by Nishisato. It is interesting to know that the recent developments in nonmetric MDS have some resemblance to those of cluster analysis, which became suddenly popular with the publication of the book by Sokal & Sneath

(1963), resulting in an enormous number of relevant publications in the latter half of the 1960's and eventually books by Cole (1969), Ball (1970), Lerman (1970), Tryon & Bayley (1970), Jardin & Sibon (197o), Anderberg (1973), Everitt (1974), and Hartigan (1975). Cluster analysis, though relevant to MDS, was omitted from the bibliography due to the massive size of the literature.

[Part II]

BIBLIOGRAPHY: MULTIDIMENSIONAL SCALING*

Shizuhiko Nishisato

*This includes a variety of multidimensional scaling techniques such as the so-called metric and nonmetric multidimensional scaling, dual scaling (optimal scaling), multidimensional unfolding, ranking and paired comparisons, and conjoint measurement analysis.

LIST OF ABBREVIATED NAMES OF JOURNALS, REPORTS AND CONFERENCES

AANT = American Antiquity
*ACSA = Paper presented at meetings of the Acoustical Society of America
ACTAP = Acta Psychologica
*AERA = Proceedings of the American Educational Research Meetings
AERJ = American Educational Research Journal
AFP = Archiv für Psychologie
AJP = American Journal of Psychology
AJPS = American Journal of Political Science
*AMA = Proceedings of the American Marketing Association Conferences
AMS = Annals of Mathematical Statistics
ANNE = Annals of Eugenics
AP = American Psychologist
*APA = Proceedings of the Annual Convention of the American Psychological Association
APM = Applied Psychological Measurement
*ASA = Proceedings of the American Statistical Association Annual Meetings
ASTAT = Applied Statistics
AUSJP = Australian Journal of Psychology
BJMSP = British Journal of Mathematical and Statistical Psychology
BJP = British Journal of Psychology
BJSCP = British Journal of Social and Clinical Psychology
BJSP = British Journal of Statistical Psychology
BORSA = Bulletin of the Operations Research Society of America
BPNS = Bulletin of the Psychonomic Society
BRMI = Behavioral Research Methods and Instrumentation
BSC = Behavioral Science
CANGE = Canadian Geographer
CJBS = Canadian Journal of Behavioral Science
CJES = Canadian Journal of Earth Sciences
CJP = Canadian Journal of Psychology
CJZ = Canadian Journal of Zoology
CONTP = Contemporary Psychology
DABSTI = Dissertation Abstracts International
DEVP = Developmental Psychology
EB = Environment and Behavior
EBB = Economics and Business Bulletin
EJMCT* = European Journal of Marketing
EPM = Educational and Psychological Measurement
IJP = International Journal of Psychology
JABP = Journal of Abnormal Psychology
JACSA = Journal of the Acoustic Society of America
JAPP = Journal of Applied Psychology
JB = Journal of Business
JBR = Journal of Business Research
JCP = Journal of Counseling Psychology
JECO = Journal of Ecology
JECP = Journal of Experimental Child Psychology
JEDUCP = Journal of Educational Psychology
JEE = Journal of Experimental Education
JEM = Journal of Educational Measurement
JEP = Journal of Experimental Psychology
JGP = Journal of General Psychology
JJB = Japanese Journal of Behaviormetrics
JM = Journal of Marketing
JMP = Journal of Mathematical Psychology
JMR = Journal of Marketing Research
JMRS = Journal of Marketing Research Society
JMRS-L = Journal of Marketing Research Society - London
JOPSA = Journal of the Optical Society of America
JP = Journal of Psychology
JPR = Japanese Psychological Research
JPSP = Journal of Personality and Social Psychology
JRSS = Journal of Royal Statistical Society
JSP = Journal of Social Psychology
JVLVB = Journal of Verbal Learning and Verbal Behavior
LS = Language and Speech
LWT = Lebensmittel-Wissenschaft-Technologie
MBR = Multivariate Behavioral Research
MMPP = Michigan Mathematical Psychology Program Technical Report
*MPM = Paper presented at the Mathematical Psychology Meetings
MS = Management Science
NIJMEGEN = Report, Department of Psychology, University of Nijmegen, The Netherlands
NTP = Nederlands Tijdschrift voor de Psychologie
OBHP = Organizational Behavior and Human Performance
OISE = Measurement and Evaluation of Categorical Data Technical Report, Department of Measurement and Evaluation, The Ontario Institute for Studies in Education, Toronto

*OPSA = Paper presented at Meetings of the Optical Society of America
OR = Operations Research
ORIRB = Oregon Research Institute Research Bulletin
ORQ = Operations Research Quarterly
PAMS = Perceptual and Motor Skills
PAP = Perception and Psychophysics
PB = Psychological Bulletin
PBEL = Psychologica Belgica
PBN = Program Bulletin, Department of Psychology, University of Nijmegen, The Netherlands
PF = Psychologische Forschung
PM = Psychological Monographs
*PMS = Paper presented at the Psychometric Society Meetings
*PNS = Paper presented at the Psychonomic Society Meetings
POPS = Population Studies
PREP = Psychological Report
PRV = Psychological Review
PS = Psychonomic Science
PSPB = Personality and Social Psychology Bulletin
QAQ = Quality and Quantity
RQ = Research Quarterly
SEPS = Socio-Economic Planning Sciences
SJM = Swedish Journal of Musicology
SJP = Scandinavian Journal of Psychology
SMR = Sociological Methods and Research
SOCQ = Sociological Quarterly
ULEIDEN = University of Leiden, Department of Data Theory Report, The Netherlands
UNCPL = University of North Carolina L. L. Thurstone Psychometric Laboratory Report
*U.S.-Japan Seminar = Paper presented at the U.S.-Japan Seminar on Theory, Methods and Applications of Multidimensional Scaling and Related Techniques, La Jolla, California, 1975.
USTOCKHOLM = Psychological Laboratories Report, University of Stockholm, Sweden
ZFEAP = Zeitschrift für Experimentelle und Angewandte Psychologie
ZFP = Zeitschrift für Psychologie
ZFS = Zeitschrift für Soziologie
ZFSP = Zeitschrift für Sozialpsychologie

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